SNAP SPECTROGRAPH:

Design Report

October 10th, 2003

1. INTRODUCTION

The SNAP spectrograph is required to identify Type Ia supernovae and to control their luminosity. It must produce for each SN candidate at peak, a confirmation spectrum. It is the best tool to understand the SN composition of the explosion and then to control and correct the magnitude if needed. The spectrograph is also an important tool for a precise spectro-photometric calibration.

2. REQUIREMENTS

To work in the SNAP environment and tag SNIa up to a redshift of 1.7, the instrument requires high throughput and broad wavelength coverage. In addition, the capability to measure simultaneously the spectra of the SNe and of the host galaxy would significantly boost the observatory performance: the galaxy subtraction would be easy and the galaxy redshift can be extracted in most of the cases. Finally, facilities on the pointing accuracy and on the calibration will be critical for a space application.

Thanks to the SN broad features, a spectrograph with a low spectral resolution is adequate enough for the SN application and will be optimized for a flat resolution $\lambda/\delta\lambda$ over the whole wavelength range. SN models indicate that parameters such as temperature, velocity or progenitor metallicity which are directly correlated to the magnitude can be extracted from the shape of the spectrum lines. The exposure time was optimized for a specified accuracy on these key parameters at the highest redshift. This leads to a spectral resolution $\lambda/\delta\lambda \sim 100$, undersampled at one pixel by resolution element. A dithering in the spectral direction will be implemented to recover the optimal sampling if needed. A detector with very low noises in the visible is required to optimize the metallicity measurement, mostly sensitive onto the UV part. Finally to measure the galaxy spectra together with the SN, a field of view of 3" is required with a spatial resolution of 0.15" small enough to cover the SN, while keeping the background contribution low.

These requirements lead to the baseline specifications shown in Table 1.

Item	Visible	IR
Wavelength coverage μm	0.35-0.98	0.98-1.7
Field of view	3.0" x 3.0"	3.0" x 3.0"
Spatial resolution element (arc-sec)	0.15	0.15
Spectral resolution, $\delta\lambda/\lambda$	100	100
Cumulative throughput	52 %	45%

Table 1: ***Spectrograph main characteristics***

3. THE INSTRUMENT CONCEPT

We are proposing an integral field spectrograph based on a reflective image slicer. After an in-depth analysis of different designs and exploration of alternatives, a trade-off analysis has been performed, balancing performances, in order to select the best possible design.

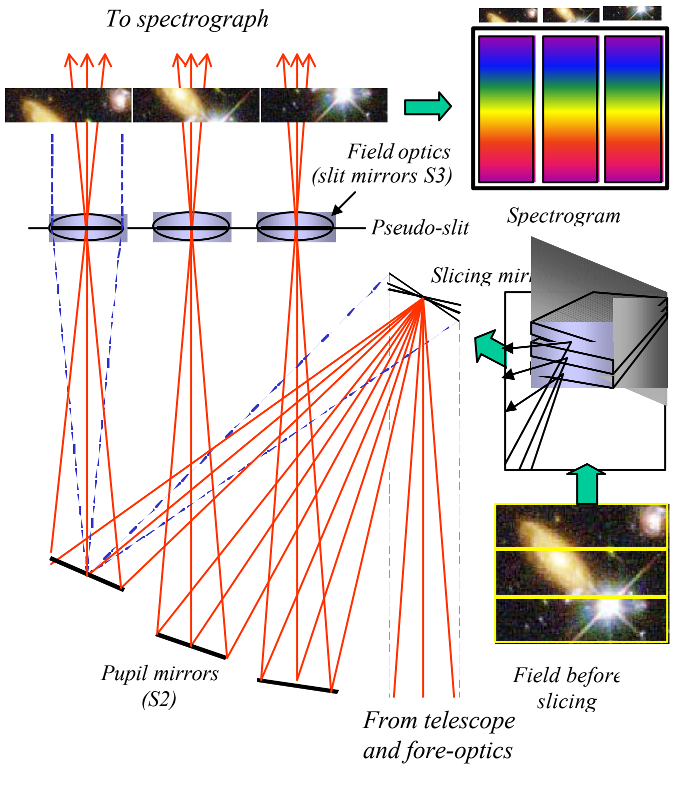


Figure 1: Image slicer principle (courtesy J. Allington-Smith, Durham U.)

Integral field spectroscopy is now a mature technique and has been used in many ground based instruments, with the latest generation being developed for 8-meter telescopes like Gemini and VLT (see *e.g.,* Bacon *et al.*, 1999; Le Fèvre *et al.*, 2000; Davies *et al.*, 1998). The principle is simple: take spectra of each resolution element in a contiguous sky area. In this way it is possible to reconstruct a 3D image on the sky (x,y,λ). We can measure at the same time the spectrum of the SNe candidate and that of the host galaxy, without slit losses and without strong requirements on the pointing capabilities of the spacecraft.

The proposed technical solution for this integral field spectrograph is based on a slicer unit (*e.g.*, NGST IFMOS study, Le Fèvre *et al.*, 1999, ASP conference series, Volume 207, 313). The basic principle is identified in Figure 1: the 2-D field of interest is "sliced" in several strips, with the slices rearranged to enter the spectrograph as the equivalent of one single long slit. This concept has several major advantages compared to a long slit spectrograph. All resolved spatial elements of a contiguous area on the sky have spectra taken; there are no slit losses; and the telescope pointing is relaxed to a fraction of the observed field, rather than being constrained to a fraction of a slit width, allowing for quick acquisition.

The instrument functionalities to be developed are summarized in the instrument block diagram shown in Figure 2. Principal components are described below.

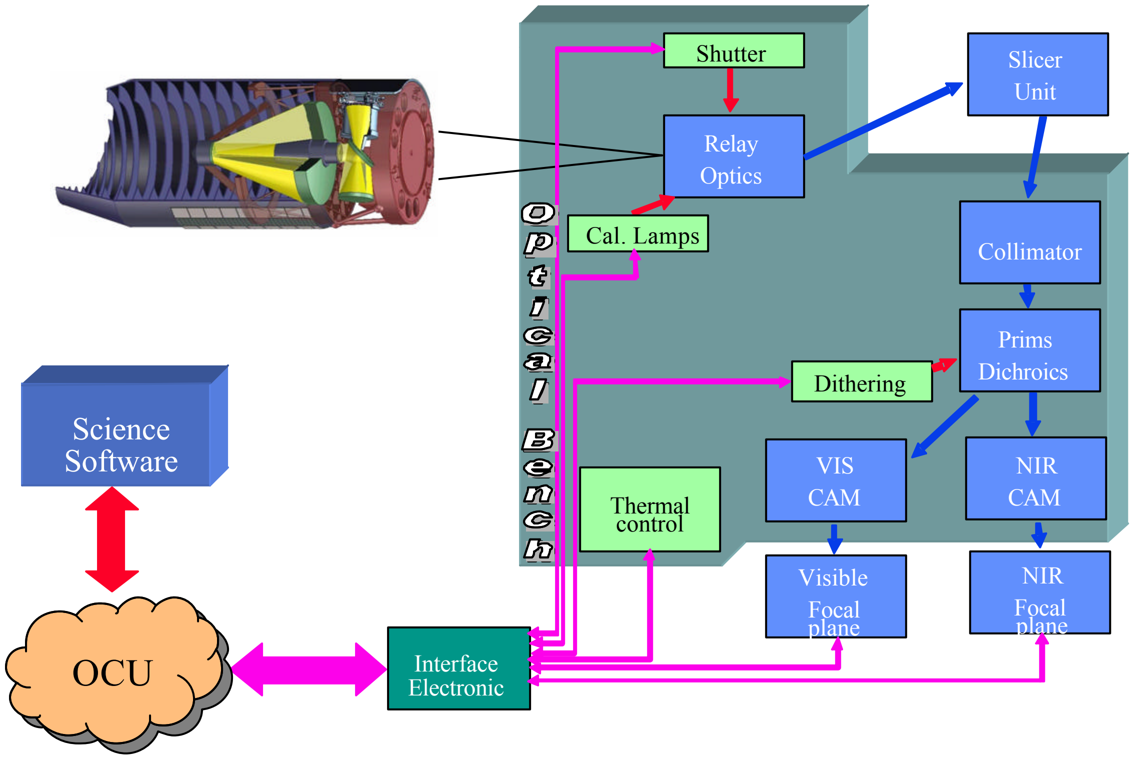


Figure 2: Instrument Block Diagram

3.1. Relay optics

This unit is the interface between the telescope beam and the instrument. The optical solution is highly dependent on the implementation of the instrument. The definition of this optical system requires the knowledge of the spectrograph position with respect to the telescope focal plane. The beam can be picked off wherever it is most convenient for the overall instrument. It will be beneficial to correct some telescope aberrations (ex: astigmatism) within this optical system.

3.2. Slicer unit

The slicer unit acts as a field reformator. The principle is to slice a 2-D field of view in long strips and optically align all the strips to a long spectrograph entrance slit. The slicing mirror comprises a stack of slicers. Each slicer has an optically active surface on one edge (see Figure 3), the active spherical surface is the first edge. A line of «pupil» mirrors does the reformatting. Each mirror sends the beam to a slit mirror, which does the pupil adaptation to the entrance of the spectrograph.

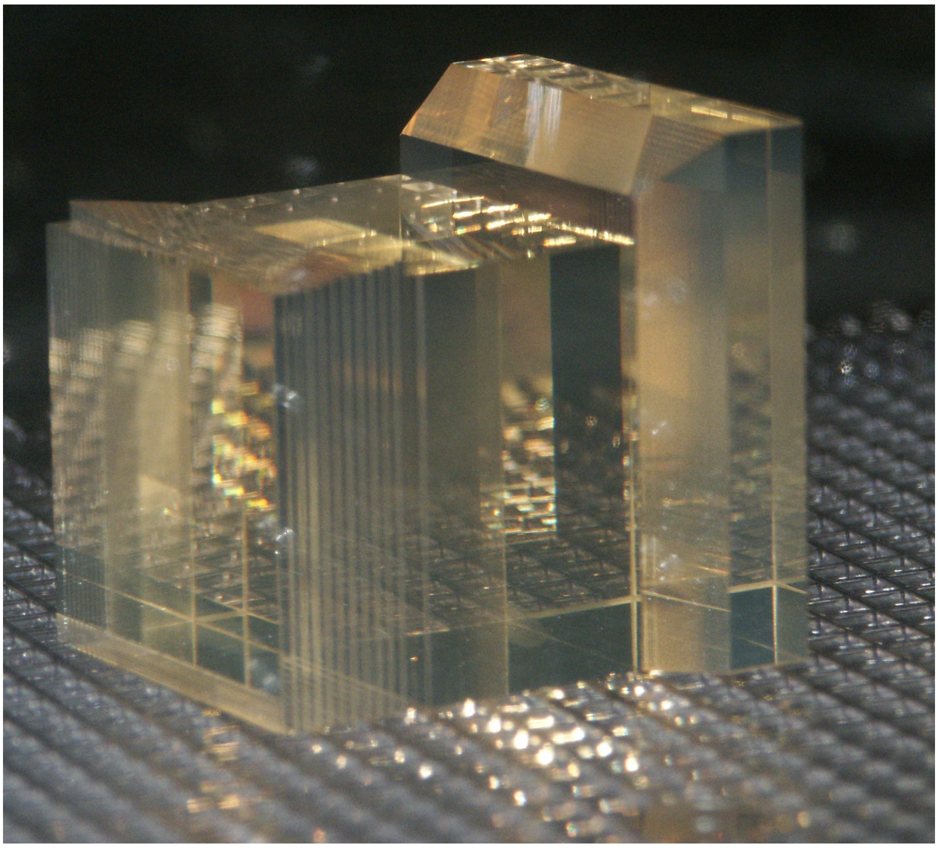


Figure 3: Picture of a block of slices

The long, thin, active surface of each individual slicer will produce a large diffraction effect. In order to minimize flux loses to a few percent, the spectrograph entrance pupil has to be oversized. A combined theoretical and experimental approach is underway at LAM to define the optimum entrance pupil.

The baseline requirements on the slicer unit are $\lambda/10$ rms on the optical surfaces and 5nm rms for the surface roughness (existing prototypes are fully compliant with these numbers).

3.3. OPTICAL BENCH.

Thanks to a small beam aperture and field-of-view, the spectrograph optics will be simple. The actual baseline is classical: one collimator mirror, one prism with a dichroic and two camera mirrors have been designed. Spherical shapes for all the mirrors would provide sharp enough image quality, but using aspherical mirrors will make it possible to have a very compact spectrograph. The prism solution is adapted to a flat resolution on the whole wavelength range. The dichroic allows to cover two channels simultaneously: one for the visible (*e.g.*, 0.3-0.98 µm) and one for the infrared (0.98-1.7 µm)

.

3.4. FOCAL PLANES

The two focal planes will be designed around the visible and IR detectors.

- In the visible, the main goals are high QE and very low noises: given concerns over degradation due to radiation exposure and the poor performance of thinned CCDs in red part of the visible, we will perform studies looking at the applicability of the LBNL CCDs. Thin backside illuminated deep depleted CCDs of 1024x1024 pixels will be the alternative option.

- For the IR, some factors limited the detector technologies: the overall temperature for the SNAP instruments will be fixed in the range [120 -140] K. The spectrograph will operate in this range. The wavelength cut-off must be as close as close as possible to 1.7 µm to reach SNAP specifications. A 1024x1024, 18.5 µm pixel HgCdTe array from Rockwell is under consideration. If too critical performances on this detector are estimated , the possibility to operate at lower temperature [100 -120] K will be investigated.

The choice and evaluation of visible and IR detectors will be done in France in relation with the teams involved in the imager to keep the simplest solution for SNAP.

A detail of the actual performance of required detectors is listed on Table 2. To achieve the listed performances on read noise and dark current, a multi sampling technique is required. The impact of the rate of cosmic rays on the readout noise is under study to optimize exposure time.

	Visible	IR
Detector size	1kx1k	1kx1k
Pixel size	10-15 µm	18.5 µm
Detector temperature(K)	140	140
QE(%)	>80	>70
Read noise(e)	2	5
Dark current(e/pixel/s)	0.001	0.02

Table 2 ***: Detector requirements***

3.5. SUMMARY OF SYSTEM REQUIREMENTS

The system requirements for each sub element are summarized on Table 3.
To avoid single point failure, the detectors will be duplicated for reliability. Two detectors will be booted in each focal plane. The field of view has been enlarged up to 3” x 6” and the number of needed slices is now of 40. This not implies any changes in the spectrograph optic.

	Visible	NIR	System description
Spatial resolution (arcsec)2	0.15		2x20 Slices 0.9 x 18 mm
Field-of-View (arc second)	3 x3		3x6
Wavelength (µm)	0.35-1.0	1.0-1.7	Dichroic
Spectral Resolution	100-200	70-100	Prism
Detector Size	1kx2k	1kx1k	800 x 200 useful 2 butted detectors
Pixel size	10-20µm	18µm	Camera F/D=12
Detector Temp (K)	140	140	Passive cooling
Function	Dithering Calibration		Dithering unit Shutter unit Lamp unit

Table 3: ***system requirements***

4. INSTRUMENT DESIGN

During last year a pre-conceptual spectrograph design has been set up and preliminary performances studied. A second iteration with more precise requirements will be done next year.

4.1. OPTICAL DESIGN

The optics has been designed to minimize the number of mirrors. This will reduce the risk but will slightly degrade the image quality. A solution with 7 mirrors is currently presented which fulfils a first volume allocation. The optical beam then reaches a BK7 prism with its back face coated with a dichroic. Visible radiation will be reflected, while infrared radiation will continue to a second prism, in CaF2 this time. The BK7 prism is used in double pass in the optical domain and this allows to reach the required dispersion with a smaller prism. The NIR beam is dispersed by the CAF2 prism in double pass at the requested R~100. Then each beam enters in the appropriated camera which images the spectrum on the visible detector in one side and on the NIR detector in the another side.
Figure 4 shows the optical layout.

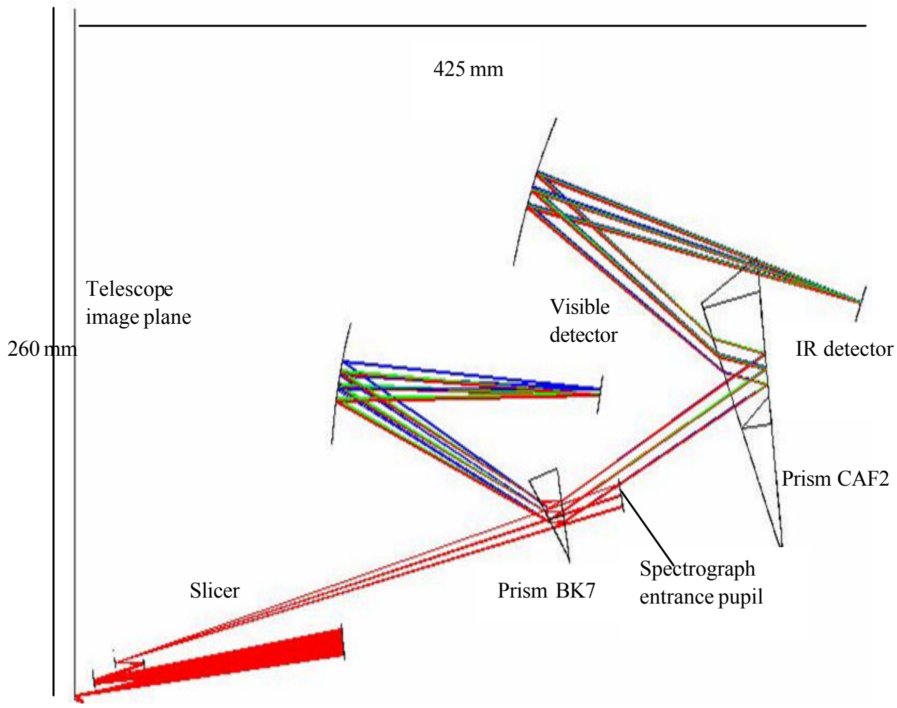


Figure 4: The optical design of the instrument

4.1.1. IMPLEMENTATION

Figure 5 shows the implementation of the spectrograph. This layout permits to see that the entrance point in spectrograph is at the border of the dark zone (interior cone in the imaging camera).
The instrument itself stands behind the large telescope imaging plane at the central place.
This configuration allows to stay away the located volume of the imaging detector and their electronics.

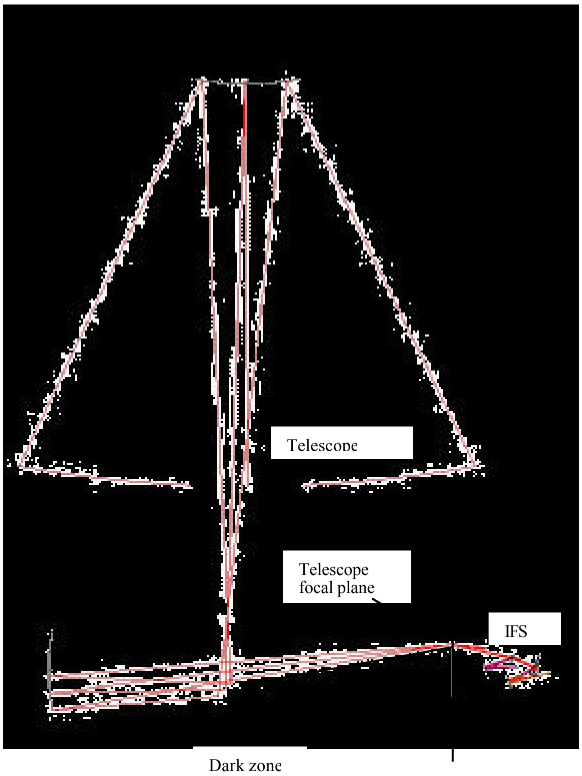


Figure 5: Spectrograph Implementation

4.1.2. OPTICAL PERFORMANCES

The current design is in agreement with the requirement on image quality. Figure 6 shows that we are diffraction limited @ 1.7µm. Thanks to simulation work, new requirements will be released and first guess is that we are currently over the next iterations in requirements.

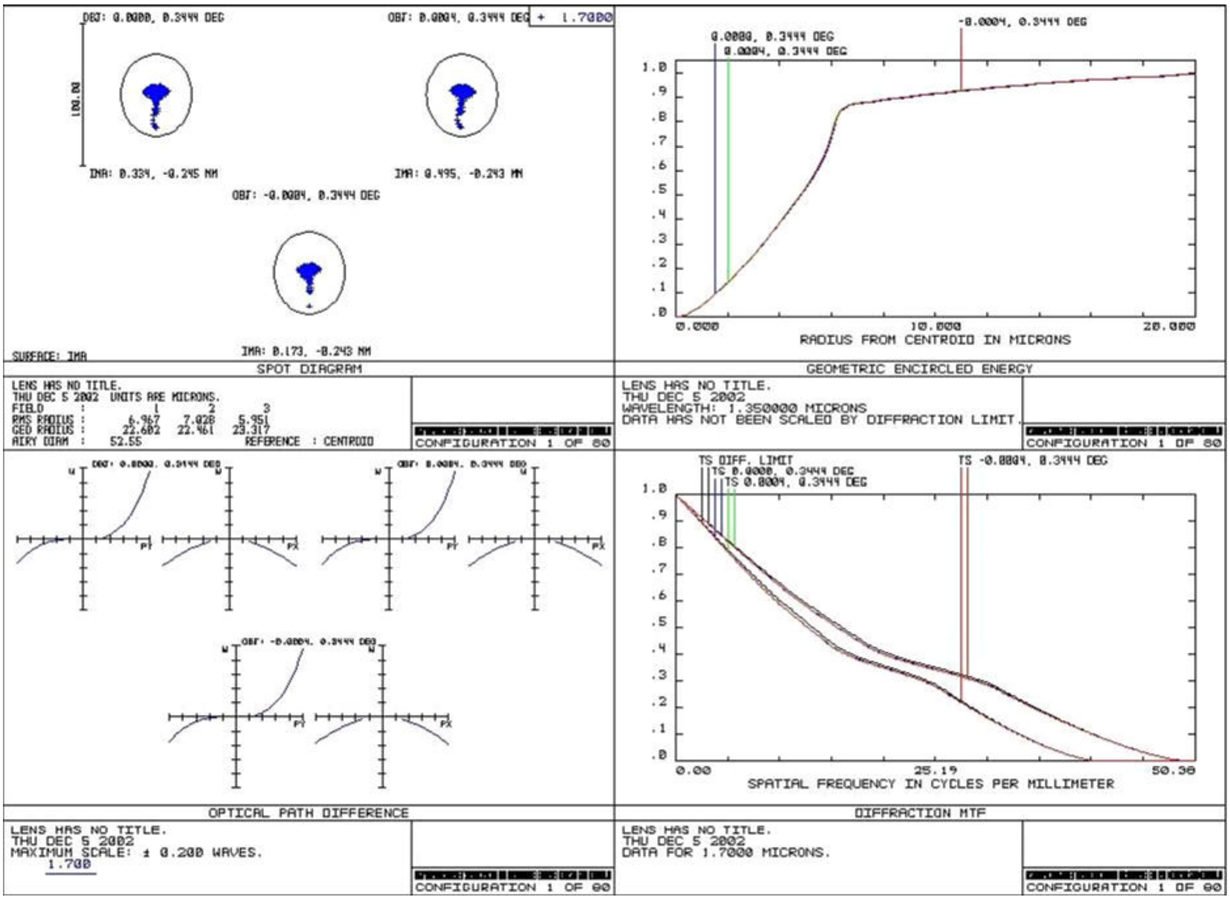


Figure 6: Image quality @ 1.7µm

4.2. MECHANICAL AND STRUCTURAL DESIGN

Figure 7 shows the implementation and a concept of mechanical structure for the spectrograph. This concept is a first base of study.

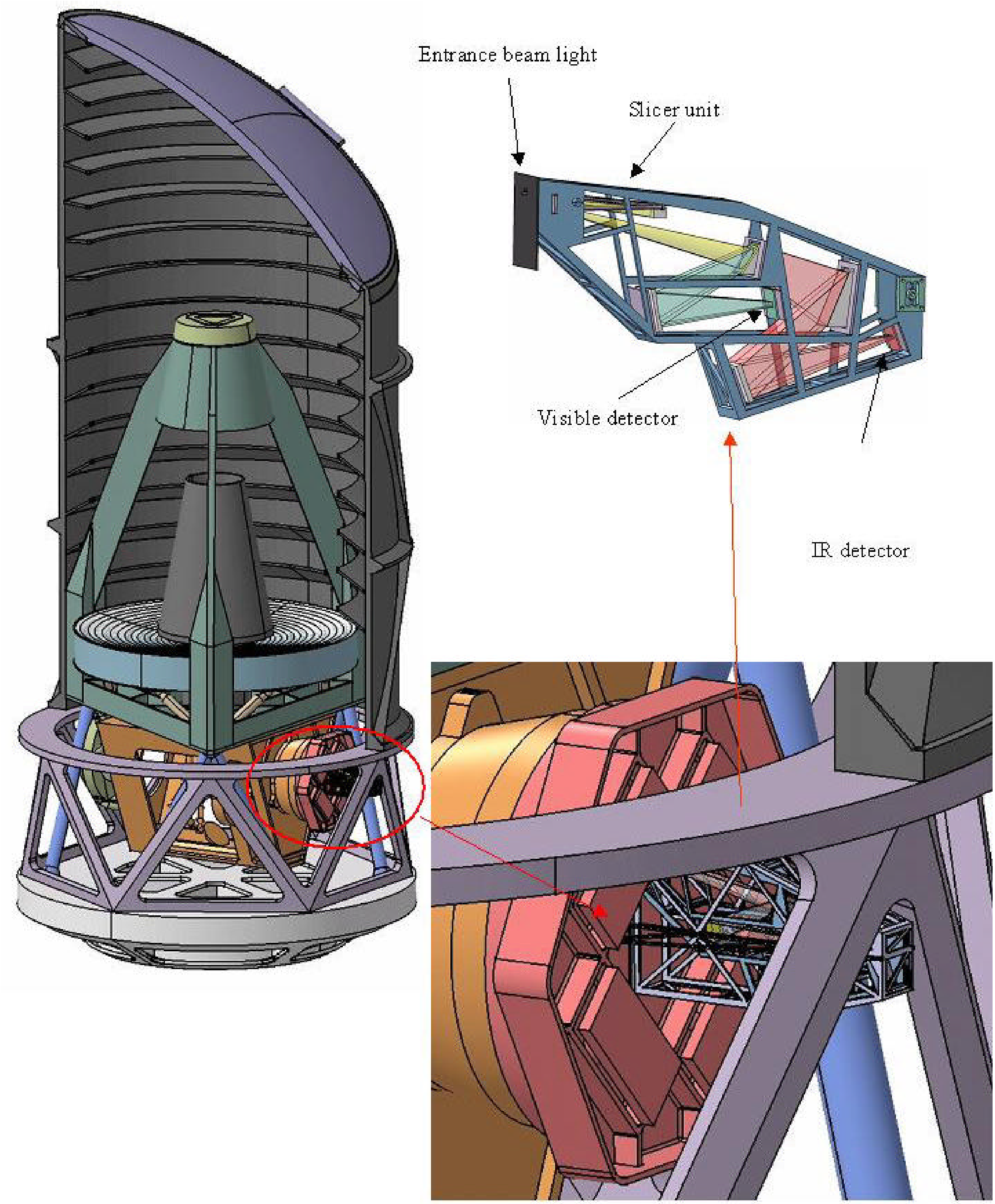


Figure 7: implementation studies

4.2.1. STRUCTURE

The choice of the material which will be determined according to its density, rigidity, thermal specific conductivity, by its ease of application but as well according to the environment and also some other criteria. A trade off will be made as shown on Table 4 .

The unquantifiable criteria are noted from A to D (A = excellent).

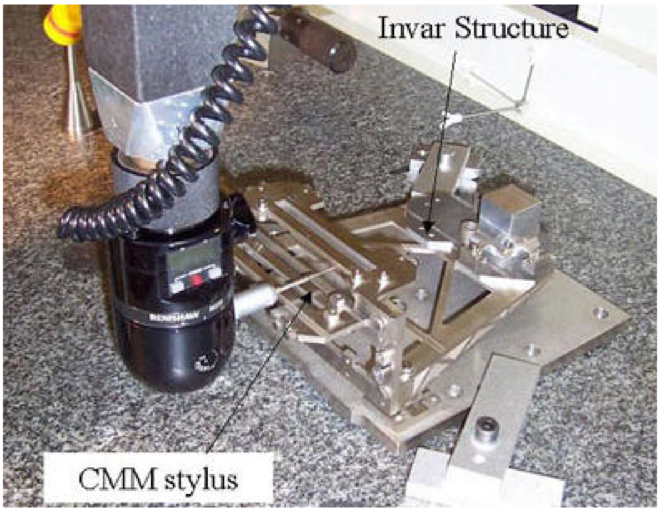
	Zérodur	Invar	Sic	Molybden um	Alu (alloy)	Beryllium
Young modulus	70 000	210 000	311 000	330 000	70 000	300 000
Density	2.2	8.1	2.9	10.2	2.7	1.9
CTE @ 300K	0.03	1.4	2.6	5.1	24	12
CTE @ 30 K	-0.7	0.3			1.5	0.1
Thermal cond. @ 300K	1.3	13.5	156	138	150	180
Manufacturing	B	A	C	B	A	B
Machining	B	A	B	B	A	C
Cost	B	B	B	B	A	C

Table 4: ***material trade -off table***

The selection of the best material will take place beginning 2004 with the design of a structure.

4.2.2. IMPLEMENTATION ADJUST AND CLAMP OPTICAL ELEMENTS

We should also define the process of adjusting and clamping all the optical elements by taking into account the material used for the optical elements but also of the temperature. For it we shall be able to serve the acquired experience on the prototype of spectrometer of type SLICER for ESA. We have, for this spectrometer developed an adjusting system by using a coordinate measure machine, and also a process of clamping with floppy elements.



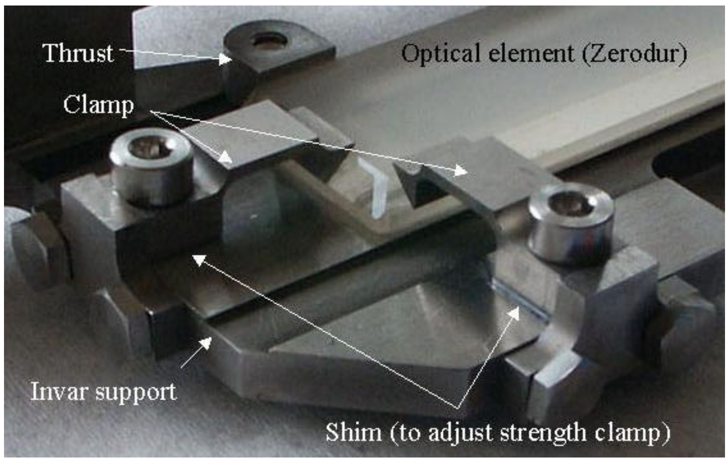


Figure 8: example of opto-mount clamping and the metrology associated

4.2.3. MECHANICAL INTERFACE WITH THE SPACECRAFT

The implementation of the spectrometer on the main structure (see the first figure of the mechanical item) should make by kinematics tree point mount, to avoid the problems of Δ CTE between the cold-plate and the material used for the structure of the spectrometer. However, a thermal coupling is necessary.
Figure 9 illustrates the philosophy of the kinematics three point mount .

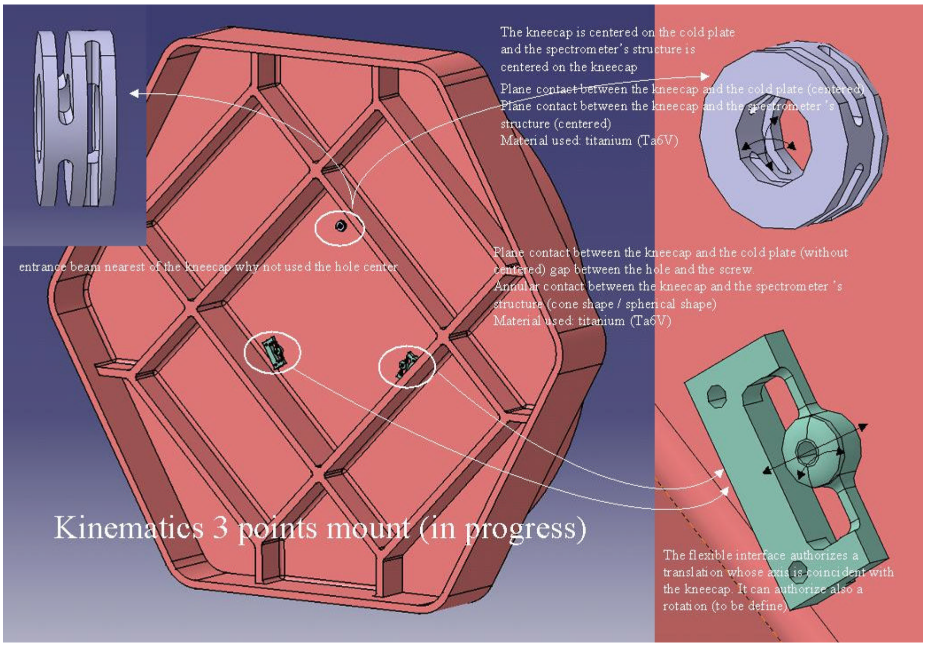


Figure 9: illustration of the mounting

The volume and position (in the SNAP's dihedral system) of the spectrometer is defined in the document. (ICD)

4.2.4. THERMAL ASPECT:

The spectrograph will be thermally coupled with the main structure of SNAP, however, we can envisage a difference of temperature for detectors if needed.

4.2.5. BAFFLING AND SHIELDING:

An optical baffling will be studied.
The radiation shield will be ensure by the global shielding of the instrument SNAP but to avoid secondary particles emission, a specific protection can be envisaged for detectors.

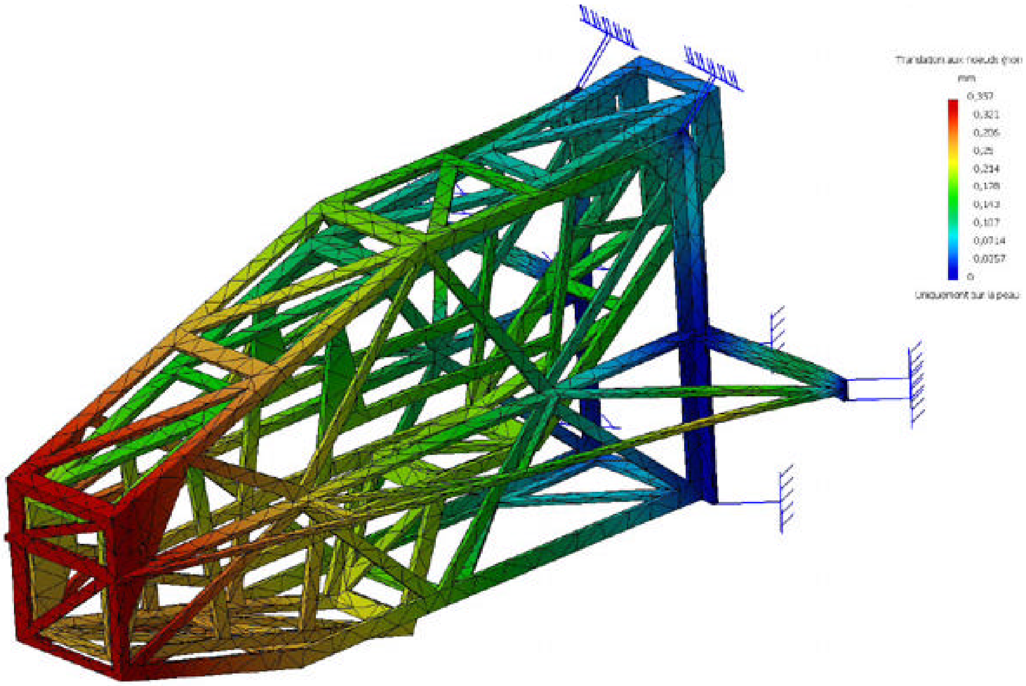


Figure 10: structure modal analysis example

4.2.6. ANALYSIS (THERMAL AND DYNAMIC):

A thermo-elastic numerical analysis of all mechanical elements of the spectrograph will be performed. It will be necessary to analyze the behaviour of the structure according to ΔT, and to verify, for example, the stability of the optical elements.

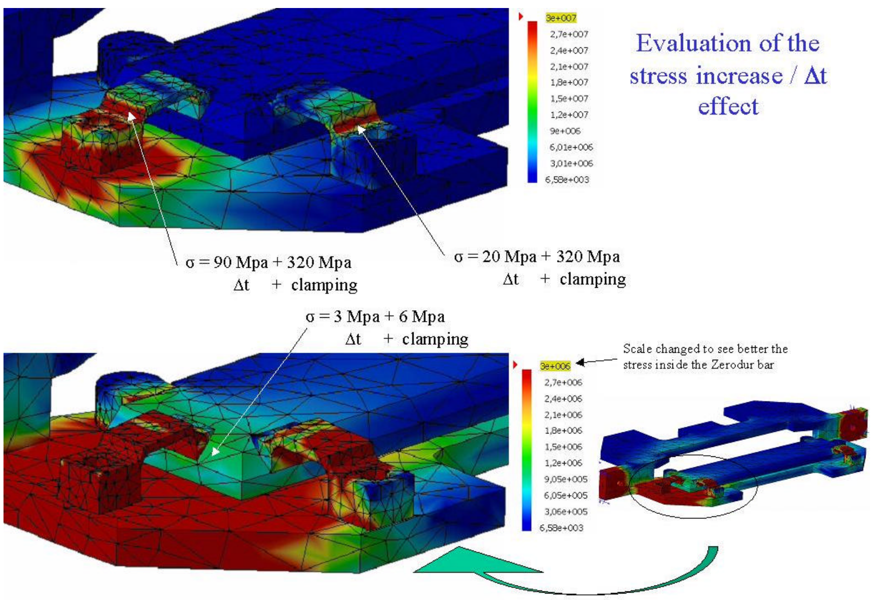


Figure 11: example of a clamping system study

Analyses (static, modal, and answer dynamics) will be made to guarantee the behaviour of the structure, the clamping system of the optical elements. Tests shall be realized (sine low level, sine qualification, and random) in agreement with the requirement. They will verify the exactness of analyses.

4.3. MECHANISM :

A spatial dithering is coming randomly through the pointing accuracy. To implement a controlled spectral dithering, a simple solution which consist at moving the prism between two fixed positions by an actuator, is under evaluation and should not be technically difficult.

4.4. FOCAL PLANE DESIGN

A focal plan definition has to be developed in the next two years to define the readout electronic and prepare the thermal and mechanical concept. To comply with the requirement of reliability, a concept of two buttable detectors has been defined and is shown on Figure 12 . A frame transfer will provide the possibility of an electronic shutter for calibration purpose .

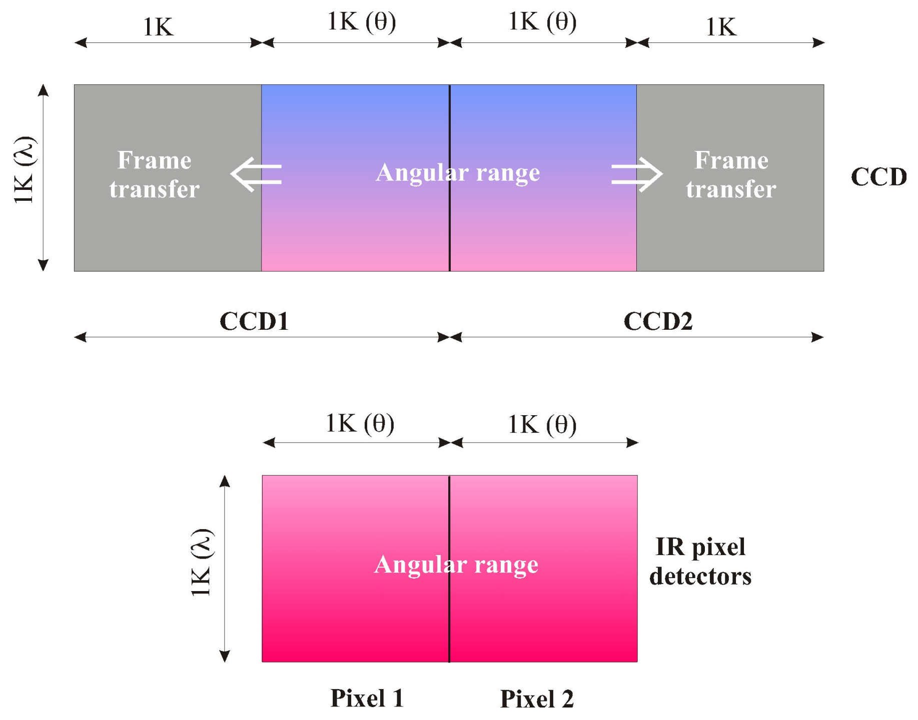


Figure 12: buttable detectors layout

5. CALIBRATION

We have produced a first calibration-oriented performance requirement document (ref ?), which sets the requirements on three of the major calibration procedures of the instrument, namely the flat-field, wavelength and absolute spectro-photometric calibrations. It is shown that wavelength calibration must have an accuracy of 20 A and that the relative spectro-photometric accuracy must be better than 1 % between the blue and red end of the spectra.
The baseline calibration procedure is classical, very similar to the one routinely used in long-slit spectrographs. The main steps are :

- ✓ apply detector calibration procedures (may include cosmic-ray rejection)
- ✓ apply flat-field calibration procedure
- ✓ correct for optical distortion of the spectra
- ✓ apply wavelength calibration procedure (may be merged with previous step)
- ✓ apply absolute spectro-photometric calibration procedure (note that this step also correct for residual slope introduced during the flat-field calibration procedure)

We can already give a preliminary list of what would be needed to calibrate the spectrograph (a more accurate list will be available once the detailed calibration error budgets will be established):

- ✓ Continuum lamp with uniform illumination over the field of view of the spectrograph (could be the lamps used for the flat-fielding of the imager).
- ✓ emission-line lamps with lines distributed over the complete spectral range (for the wavelength calibration)
- ✓ small-step dithering capability at observatory level for spectral point-spread function stability (to average out the so-called slit effect).
- ✓ at instrument level, it might be necessary to implement spectral dithering (by tilting mechanically the prism)
- ✓ Set of spectro-photometric standard stars for the absolute flux calibration of the instrument.
- ✓ Possible need for a mechanical or electronic (i.e. using charge transfer forward an unexposed part of the detector) shutter to allow short exposure times on bright calibration stars.

6. SOFTWARE DEVELOPMENT

A full simulation of the optical system has been developed, based on Fourier optics. It is coupled to the detailed design of the instrument via Zernike coefficients produced by the Zemax program. The output is a discrete psf at the detector level, for a monochromatic point source at a given position.

It has been used to simulate a complete SN spectrum in the 0.35-1.7 um range (see Figure 13), and to verify that the expected performances can be reached. Spectral resolution and Spectrograph + telescope throughput have been verified.

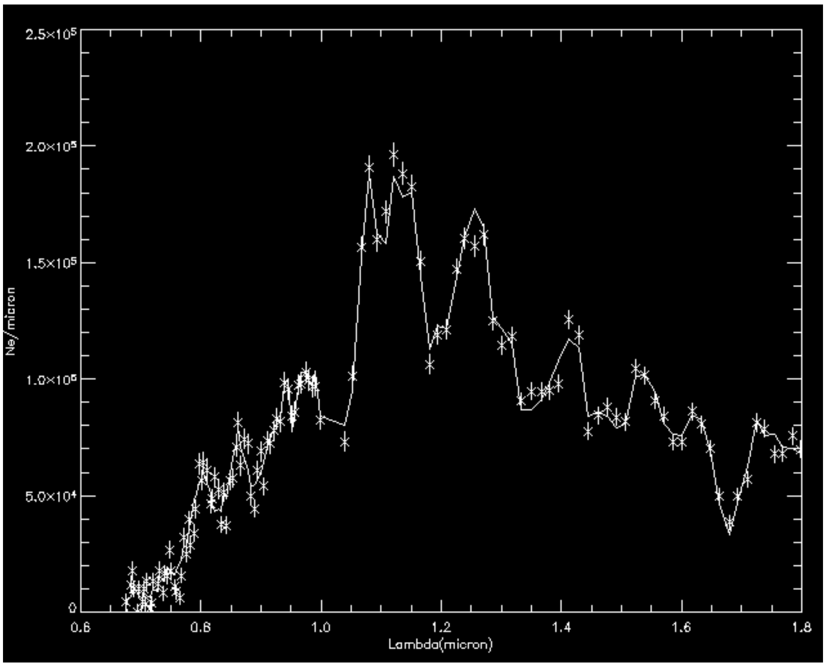


Figure 13: simulated calibrated spectrum

This approach is not practical for more extensive studies, because of the large variety of discrete psf representations needed. To solve this problem, a parametrization based on shapelets decomposition of the psf is currently developed. First results show that the required accuracy can be reached with a limited number of eigen functions. Cpu time necessary for the reconstruction is manageable and the volume of data is now very small. We have written a java implementation of the shapelets library (A.Refregier, R. Massey).

7. PERFORMANCES

7.1. SPECTRAL RESOLUTION

The spectral resolution is shown on Figure 14 and has been optimised to be maintained as flat as possible, privileging lower values in the IR region. The detailed simulation has been used to confirmed this resolution.

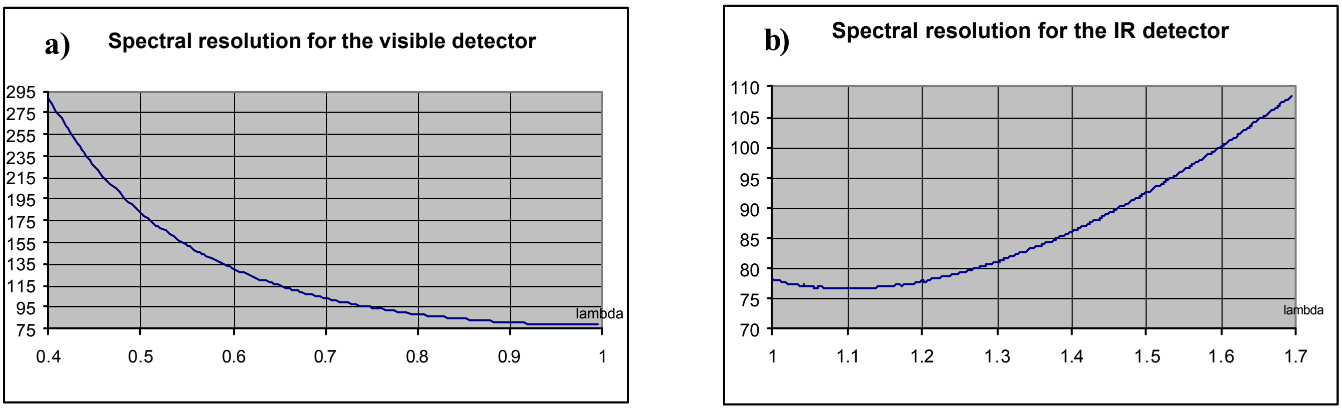


Figure 14: a) spectral resolution a) in the visible **b) in the IR**

7.2. THROUGHPUT

The estimated throughput of the instrument is given on Table 5. Thanks to the good throughput of the reflective silver coated optic and to the slicer performance, the expected total throughput of the instrument is 3 to 4 time higher than the HST-STIS one. To derive this table, the full simulation of the slicer and the spectrograph has been used included the diffraction and aberration effects on each optical plane.

	# elements	Efficiency /elements	Cumulative efficiency
Telescope	4	0,98	0.92
Relay optic	1	0,98	0.90
Slicer (mirrors+straylight+diffraction)		0.82	0.71
Spectro	Mirrors 2 Prism Dichroic	0.98 0.81 0.95	0.57
Detector vis	1	0.9	0.52
Detector IR	1	0.8	0.42

Table 5: instrument efficiency estimation

8. RISK ASSESSMENT

Our preliminary analysis indicates that the image slicer and the detectors are the only components requiring effort during the R&D phase to mitigate risk later in the project. All other components are well within the current technology.

9. INSTRUMENT DEVELOPMENT ROAD MAP

After a trade off study, a pre conceptual design has been developed which has been used to prove the feasibility and the adaptation of this technique to the SNAP mission. The detailed simulation which is under development has been used to prove the high level performances of the optical system. High level requirements have to be finalized based on the science specifications.

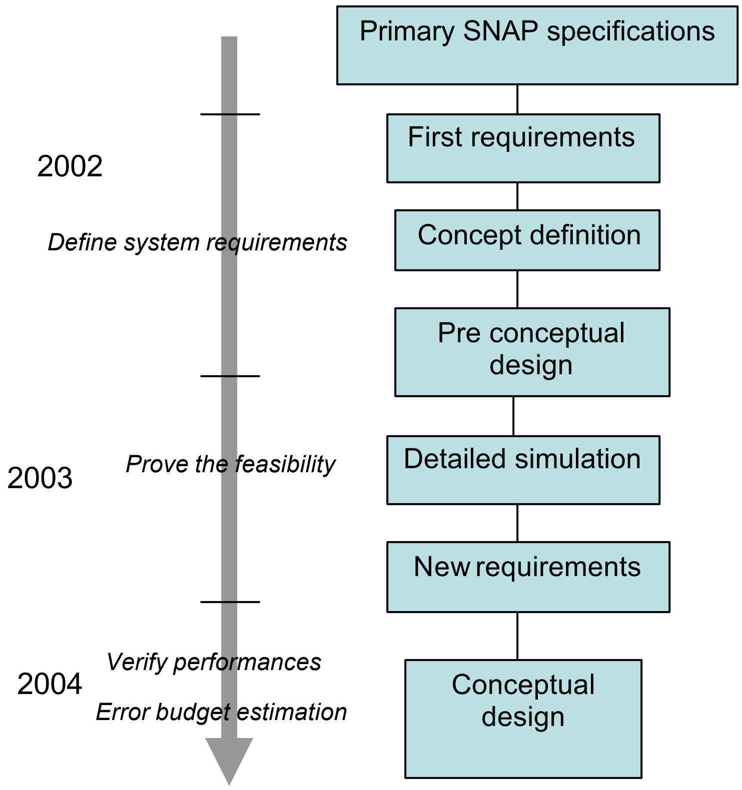


Figure 15: spectrograph development roadmap

Concept development

Figure 15 shows the instrument development roadmap. The detailed technical requirements are under study and will be finalized in the next year, taking into account the simulation results and the calibration studies. Preliminary interface definitions have been set (ICD 00026 - MW02 - A 2003-09-16) and will be pursue in the next months. A new instrumental concept will be designed. The main technical change will be a new definition of the allocated envelop for the spectrograph itself. A new envelop shorter than the previous one is proposed, but no difficulty are foreseen, thanks to the addition of one mirror more in the spectrograph.

Software development

A full implementation of the spectrometer simulation will be pursued. A parameterisation of the shapelet coefficients as a function of spatial position and wavelength will be established. The combination with the shapelet decomposition of galaxies will be explored, in order to simulate realistic data cubes for a SN and its companion.
The development of the data reduction procedure will start. We expect that it will continue during several years. We will rely on the work of the EUro3D consortium, which develops general purpose utilities for integral field spectrometers. Customization to SNAP will nevertheless require significant efforts.
The precise and detailed simulation of the instrument and associated physics analyses will validate the final design at the end of the R&D phase.

Calibration

Calibration strategy will be further developed: we will detail each of the calibration procedures and build the corresponding error budgets. We will then define calibration scenarios (on-the-ground calibration prior to launch; initial calibration campaign immediately after launch; routine calibration sequences) and derive stability requirements for the instrument and observatory (feed-back to the opto-mechanical design). These detailed calibration scenarios will be used as inputs to the operation of the instrument, in particular to estimate the operational efficiency of the instrument.

10. R&D ACTIVITIES

Two main activies have been identified as R&D studies for the two next years: One on the slicer to achieve a TRL 6 (space environment) level and to adapt the actual technique to SNAP, the other on the focal plane development of the detectors to validate the performances with the chosen technologies.

10.1. SLICER R&D

The proposed image slicer is of the same type as the one studied in the context of the NGST near-IR spectrograph (Allington-Smith *et al*., 1999; Le Fèvre *et al*., 1999). This technology has been ranked at NASA readiness level 5 by a panel of NASA experts in the context of the concept appraisal of pre-phase A NGST studies. The readiness level 6 is required to be "space qualified." .Prototyping activities are on-going at Laboratoire d'Astrophysique de Marseille (LAM) and in collaboration with other European institutes to validate this technology both for large ground-based telescopes and for space applications, under funding by various agencies including ESA, CNRS and CNES. The R&D effort necessary to adapt this concept to the SNAP requirements therefore meshes in nicely with on-going activities and will be in time with the R&D phase.

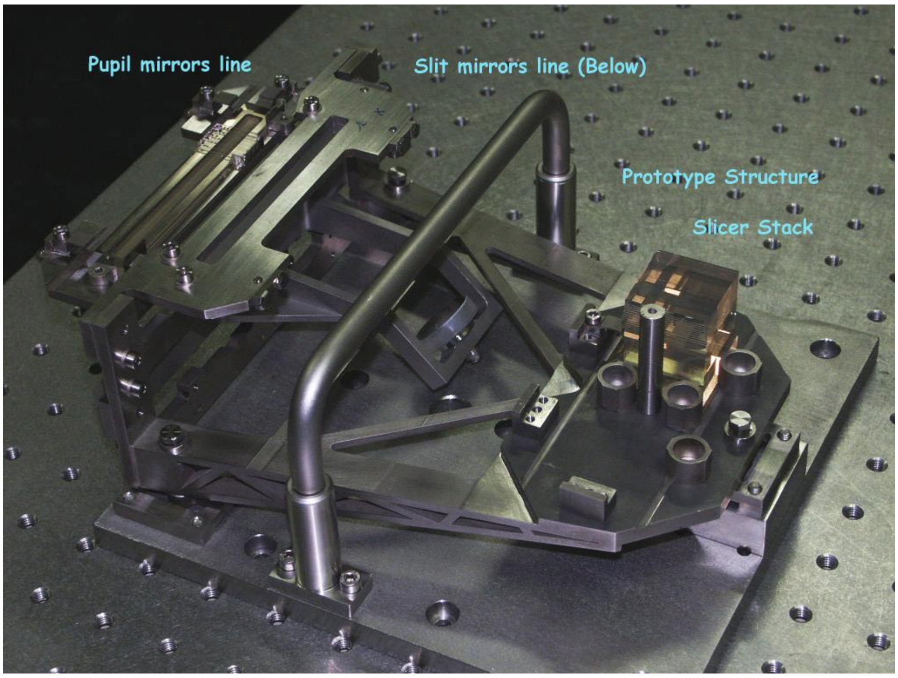


Figure 16: slicer prototype integrated

Specifically, we have an on-going program to qualify image slicers for space instrumentation. We are now in the process of developing a realistic prototype for a space-qualified unit, based on Zerodur-glass slices. By the end of 2003 Image slicers' technology will be ranked at TRL 6. We are currently integrating the prototype and will conduct a set of test for its qualification. Visible test at room temperature will permit to completely understand the optical behaviour of this technology. Afterward 30°K test run will be run in order to check the performance at cryogenic temperature. Vibration test with Ariane 5 specifications will prove the survival to launch.
All principal technology are identical for SNAP, except very few parameter (temperature,…). Some prototype works will be done during the two next year for complete validation for the SNAP case. Figure 16 shows the prototype integrated end ready for the test run.

10.2. DETECTOR R&D

A dedicated R&D in France, supported by IN2P3/CNRS, will develop the expertise on the acquisition electronics of IR detectors (E.Barrelet/G.Smadja and all.). It will evaluate the different CCD technologies for the spectrograph and the optimisation of the design. Afterward, the solution adopted by SNAP will be tested and fully characterized at the end of the R&D phase.
Output document will be a development plan for phase B/C/D.
As the impact of various sources of noise is critical for the good performance of the spectrograph a large fraction of the efforts in 2004 will be dedicated to the electronic noise minimisation.

Developments include a first conduct of expertise study for detector and electronic :

- For the detector, benches for test purpose are under development and have been ordered for optical and IR. An H1RG Rockwell detector has been ordered and is expected to be delivered January 2004. A Dewar (80K-140K°) will be fabricated which includes accurate temperature monitoring and monitoring photodiode allowing to test the Rockwell detector in the wanted temperature range (leakage currents, readout noise, homogeneity, intrapixel variations, clock frequency, optimisation of multi read scheme). A particular attention will be given to the understanding of the 1/f noise. Concerning the CCD evaluation, a Deep Depleted EEV CCD will be evaluated with emphasis on fringing tests and efficiency.

- The activities on the electronic development are reported elsewhere and concern ASIC development in collaboration with the LBNL group with a contribution to a radhard CCD front end and the development of an ASIC modelled on the MEGACAM front end architecture. The MEGACAM-like ASIC for CCD readout will be tested and a readout demonstrator for IR pixels (FPGA+ microprocessor) will be constructed.

11. R&D DELIVERABLES

Table 6 lists deliverables generated during the R&D effort.

Table 6. Spectrograph deliverables schedule.

Deliverable	Completion Date
Performance requirements	November-2003
Science and Technical trade study	November-2003
Spectrograph pre-conceptual design	November-2003
Focal plane concept review	May-2004
Slicer Prototype report	May-2004
Conceptual design report	November-2004
Construction cost and schedule	February-2005